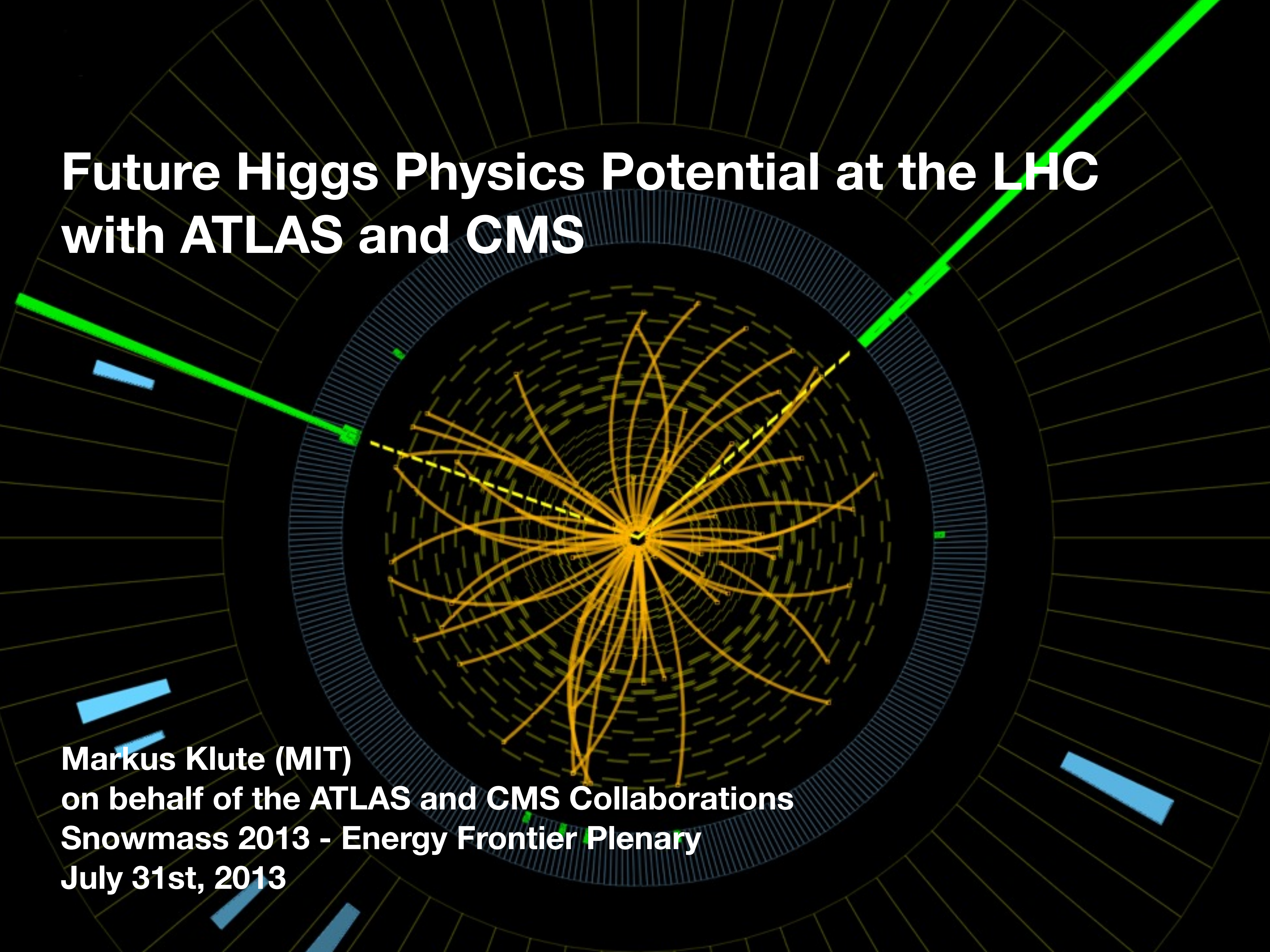


Future Higgs Physics Potential at the LHC with ATLAS and CMS

Markus Klute (MIT)
on behalf of the ATLAS and CMS Collaborations

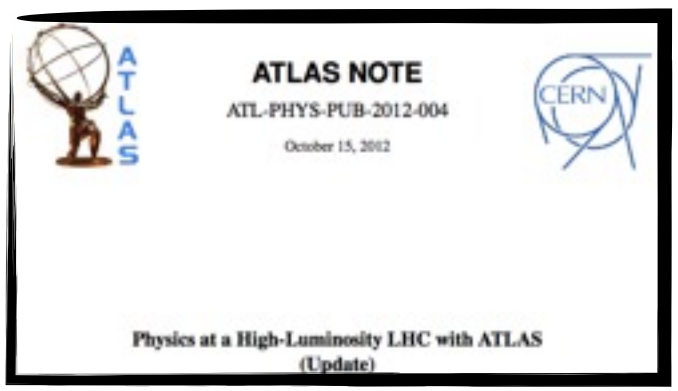
Snowmass 2013 - Energy Frontier Plenary

July 31st, 2013

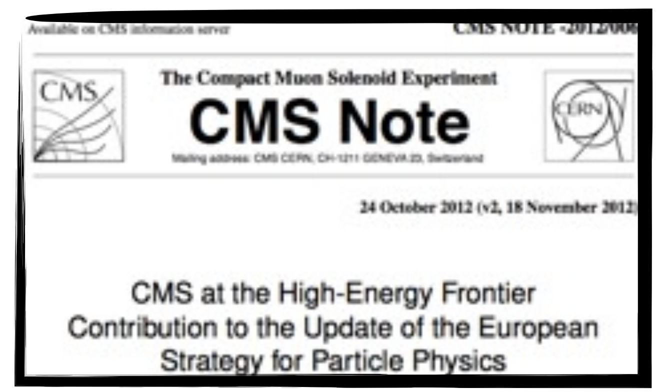
Roadmap for Future Projections

European Strategy Preparatory Group (ESPG)

Updated proposal for the European strategy for particle physics.
ATLAS and CMS submitted documents summarizing potential physics reach for LHC14 (300fb-1), HL-LHC (3000fb-1).


ATLAS NOTE
ATL-PHYS-PUB-2012-004
October 15, 2012

Physics at a High-Luminosity LHC with ATLAS
(Update)

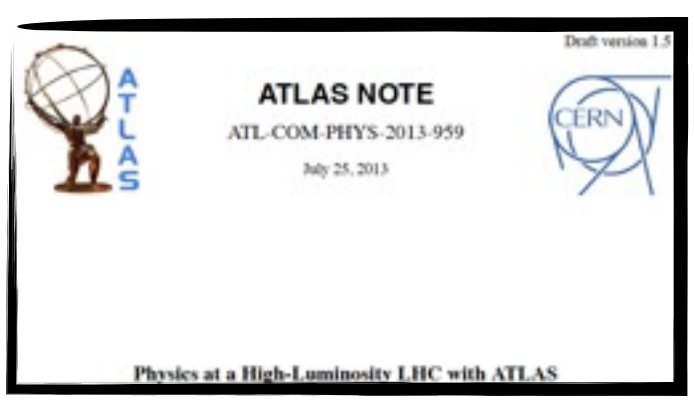

The Compact Muon Solenoid Experiment
CMS Note

24 October 2012 (v2, 18 November 2012)

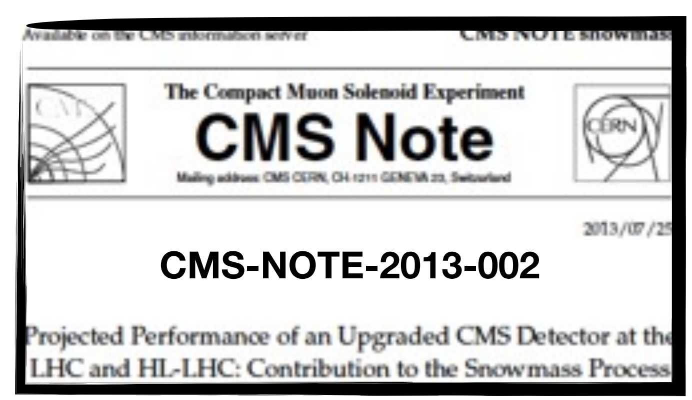
CMS at the High-Energy Frontier
Contribution to the Update of the European
Strategy for Particle Physics

ATLAS submitted a Phase-II letter of intend in March 2013.

For Snowmass, ATLAS and CMS updated and extended ESPG studies.


Draft version 1.5
ATLAS NOTE
ATL-COM-PHYS-2013-959
July 25, 2013

Physics at a High-Luminosity LHC with ATLAS


The Compact Muon Solenoid Experiment
CMS Note

CMS-NOTE-2013-002

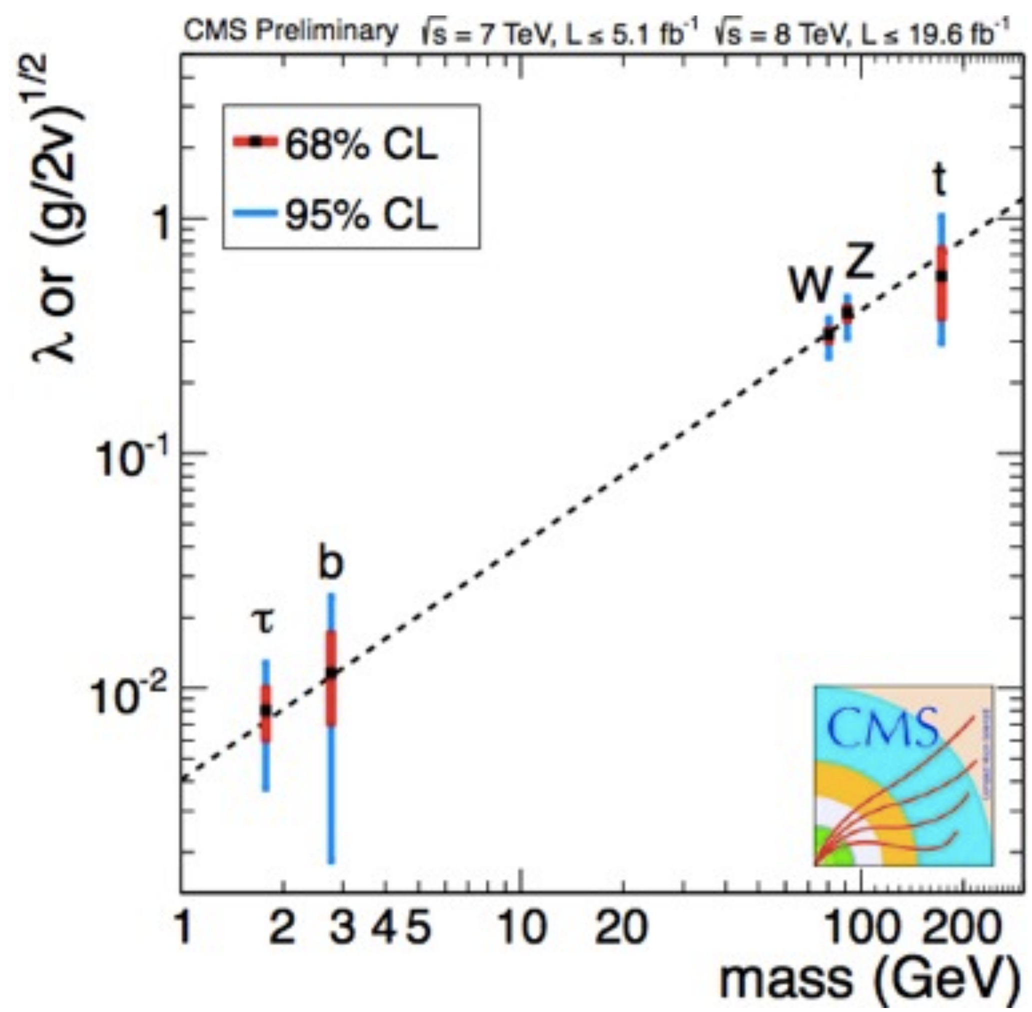
Projected Performance of an Upgraded CMS Detector at the
LHC and HL-LHC: Contribution to the Snowmass Process

Next set of results planed for ECFA HL-LHC workshop Oct. 2013.

Status of Higgs Studies at the LHC

Fantastic progress since discovery July 2012

- Observation in three bosonic channels
- Evidence for fermion couplings
- Precision mass measurement
- Spin determined
- **Looks more and more like the SM Higgs boson**
- No evidence for non-SM decays
- No evidence for additional Higgs bosons



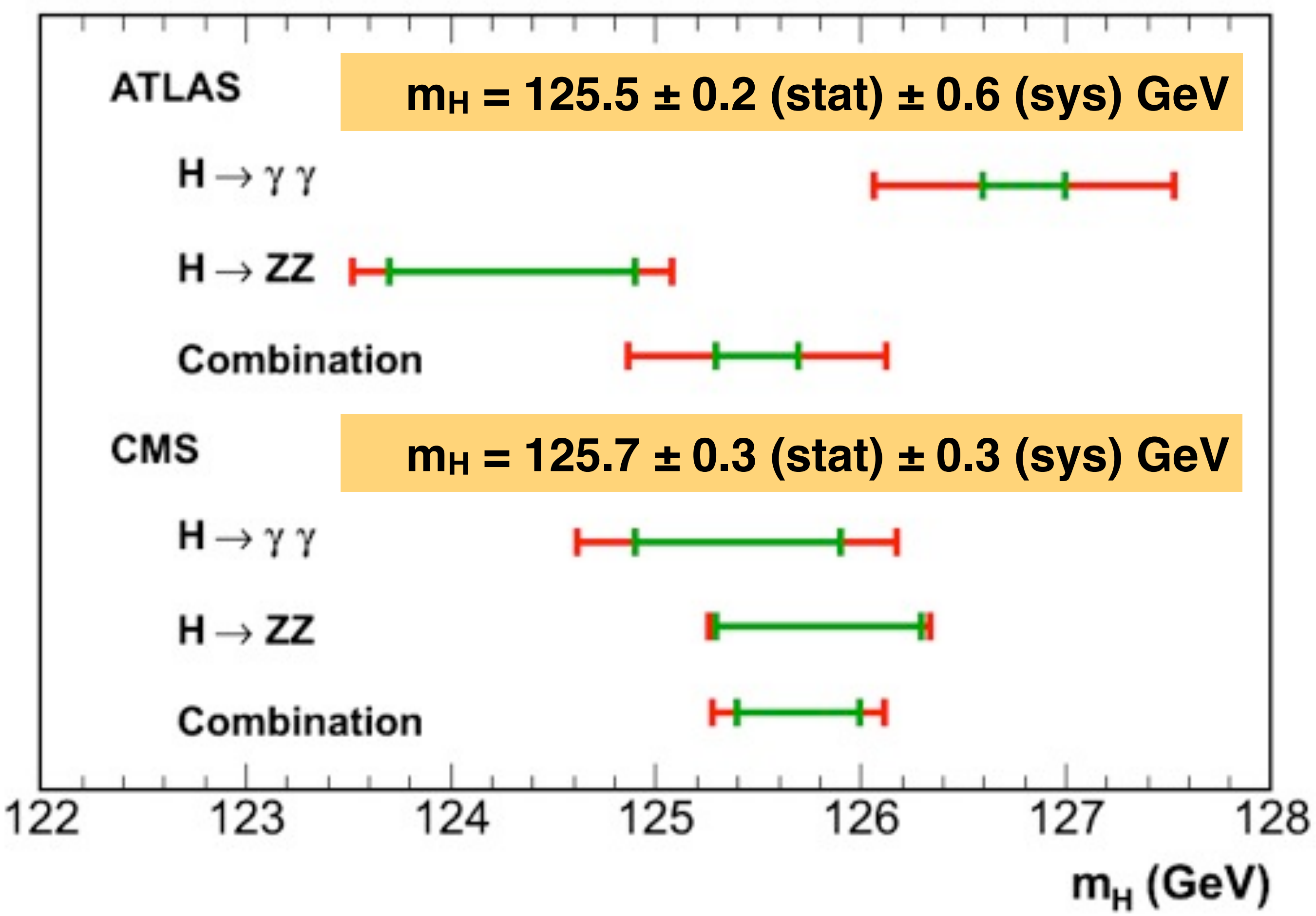
Questions (see Beate's talk)

- Is it the Higgs boson?
  - Does it couple to matter exactly as predicted?
  - Does it couple to gauge bosons exactly as predicted?
- Are there more Higgs bosons?
- Does the Higgs boson decay to non-SM particles?
  - E.g. to Dark Matter?
- ...

Discovery opened a new era of Higgs measurements

Higgs Boson Mass Measurement

High resolution channel H → γγ and H → ZZ* → 4l



ATLAS 115 GeV < m_{4l} < 125 GeV

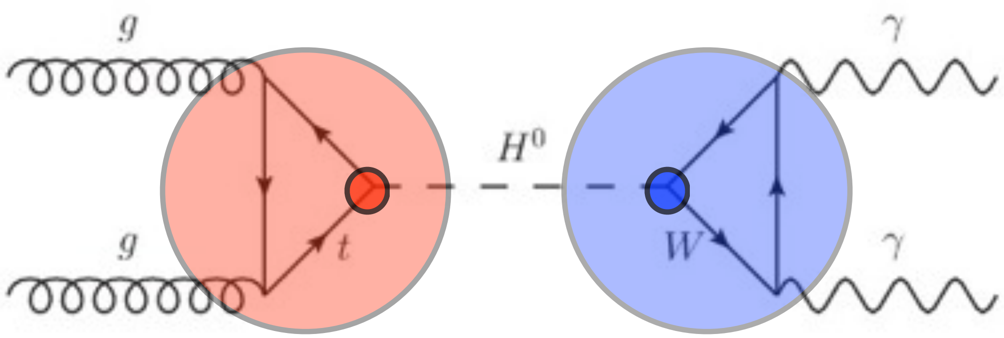
	total signal full mass range	signal	$ZZ^{(*)}$	$Z+\text{jets}, t\bar{t}$	S/B	expected	observed
4μ	6.8 ± 0.8	6.3 ± 0.8	2.8 ± 0.1	0.55 ± 0.15	1.9	9.6 ± 1.0	13
$2\mu 2e$	3.4 ± 0.5	3.0 ± 0.4	1.4 ± 0.1	1.56 ± 0.33	1.0	6.0 ± 0.8	5
$2e2\mu$	4.7 ± 0.6	4.0 ± 0.5	2.1 ± 0.1	0.55 ± 0.17	1.5	6.6 ± 0.8	8
$4e$	3.2 ± 0.5	2.6 ± 0.4	1.2 ± 0.1	1.11 ± 0.28	1.1	4.9 ± 0.8	6
total	18.2 ± 2.4	5.9 ± 2.1	7.4 ± 0.4	3.74 ± 0.93	1.4	27.1 ± 3.4	32

CMS 110 GeV < m_{4l} < 160 GeV

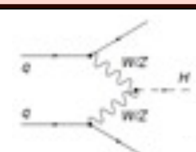
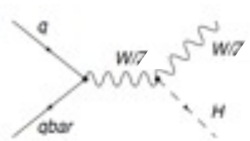
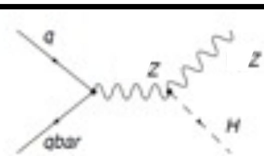
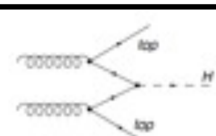
Channel	4e	4μ	$2e2\mu$	4ℓ
ZZ background	6.6 ±0.8	13.8 ±1.0	18.1 ±1.3	38.5 ±1.8
Z+ X	2.5 ± 1.0	1.6 ± 0.6	4.0 ± 1.6	8.1 ±2.0
All background expected	9.1 ± 1.3	15.4 ± 1.2	22.0 ± 2.0	46.5 ± 2.7
m_H = 125 GeV	3.5 ±0.5	6.8 ±0.8	8.9 ±1.0	19.2 ±1.4
m_H = 126 GeV	3.9 ±0.6	7.4 ±0.9	9.8 ±1.1	21.1 ±1.5
Observed	16	23	32	71

Δm of 100(50) MeV achievable for 300(3000) fb^{-1}

Higgs Precision Measurements



m_H = 125 GeV

Process	Diagram	Cross section [fb]	Unc. [%]
gluon-gluon fusion		19520	15
vector boson fusion		1578	3
WH		697	4
ZH		394	5
ttH		130	15

m_H = 125 GeV

Decay	BR [%]	Unc. [%]
bb	57.7	3.3
ττ	6.32	5.7
cc	2.91	12.2
μμ	0.022	6.0
WW	21.5	4.3
gg	8.57	10.2
ZZ	2.64	4.3
γγ	0.23	5.0
Zγ	0.15	9.0
ΓH [MeV]	4.07	4.0

* uncertainties need improvements for future precision measurements

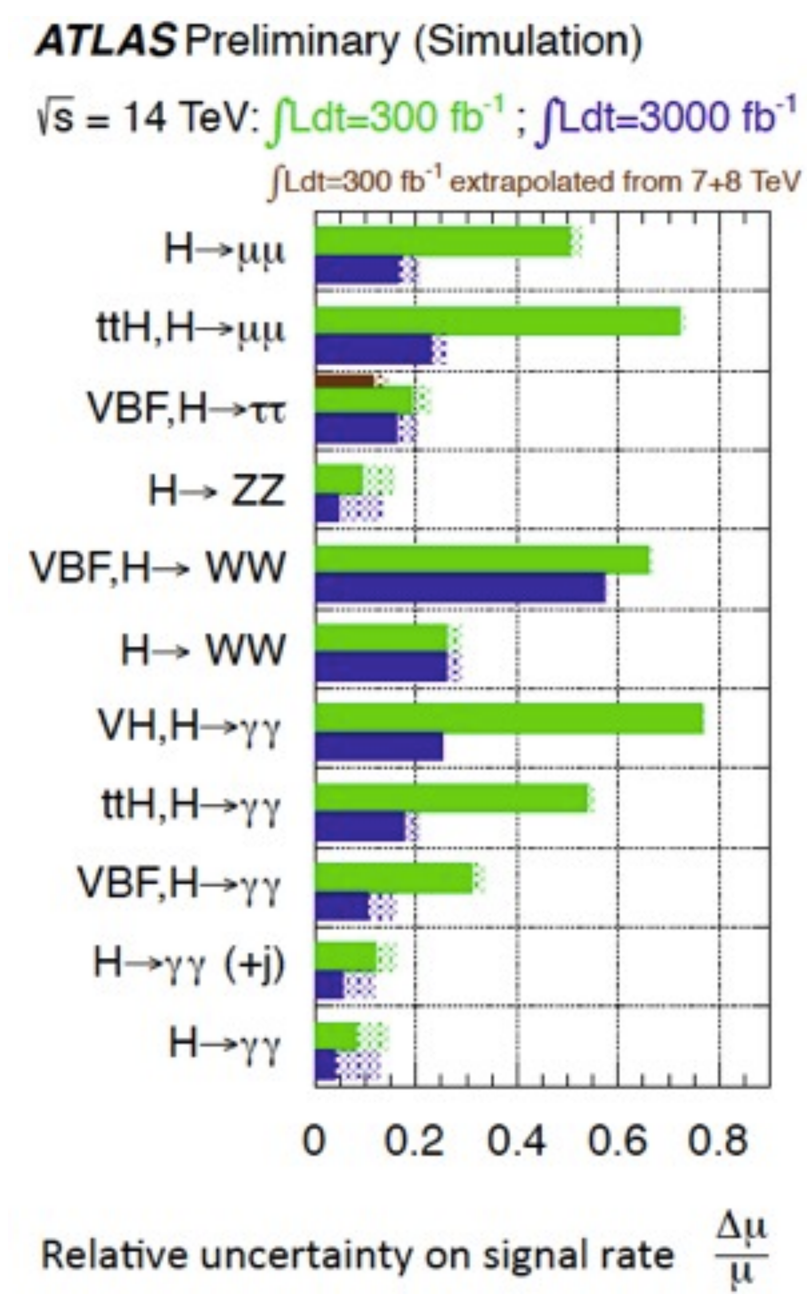
Sensitive Higgs Channels - Table of Inputs

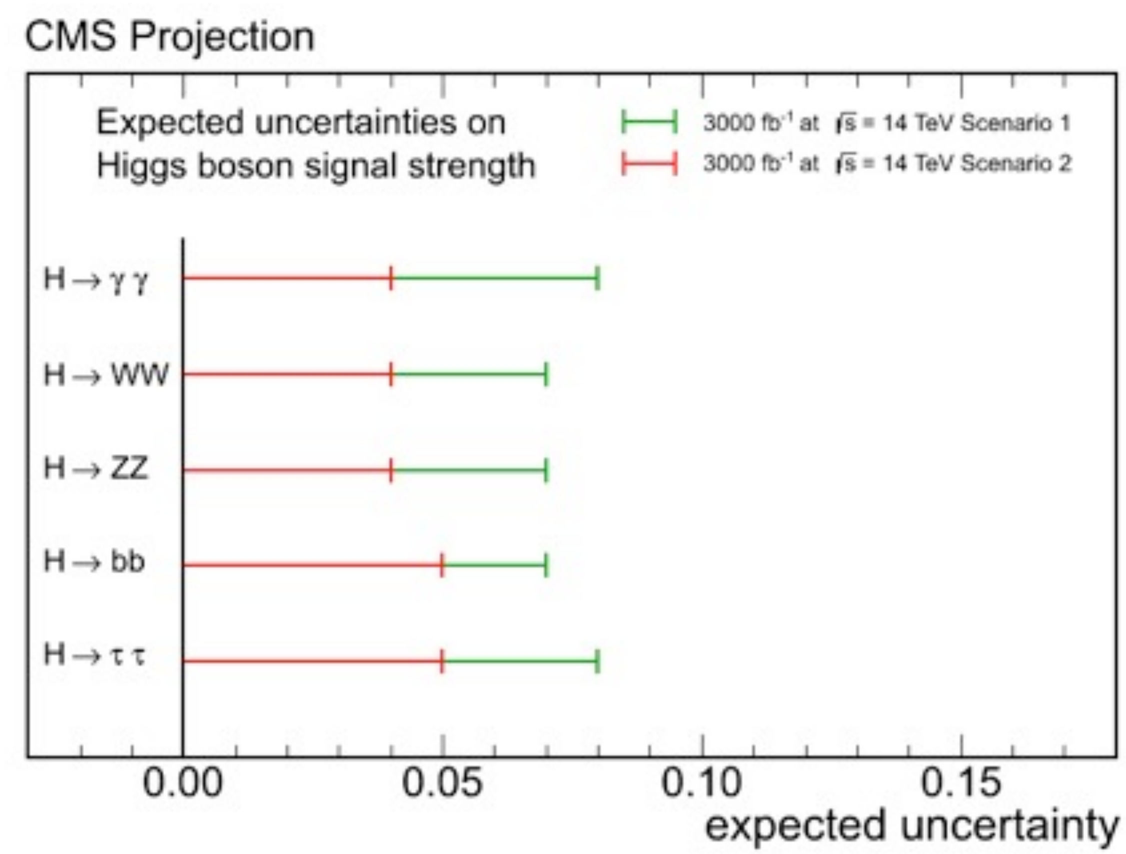
	untagged	jet-tag	VBF	VH	ttH
$H \to \gamma\gamma$	used				
$H \to WW \to 2l2\nu$					1307.7280
$H \to ZZ \to 4l$		possible			
$H \to bb$					
$H \to \tau\tau$					
$H \to Z\gamma$					
$H \to \mu\mu$					
$H \to$ invisible					
$H \to HH$					

Measure rate of Higgs events with different production and decay combinations.

Cross-contamination of production and decay channels in categories.

Uncertainty on Signal Strength





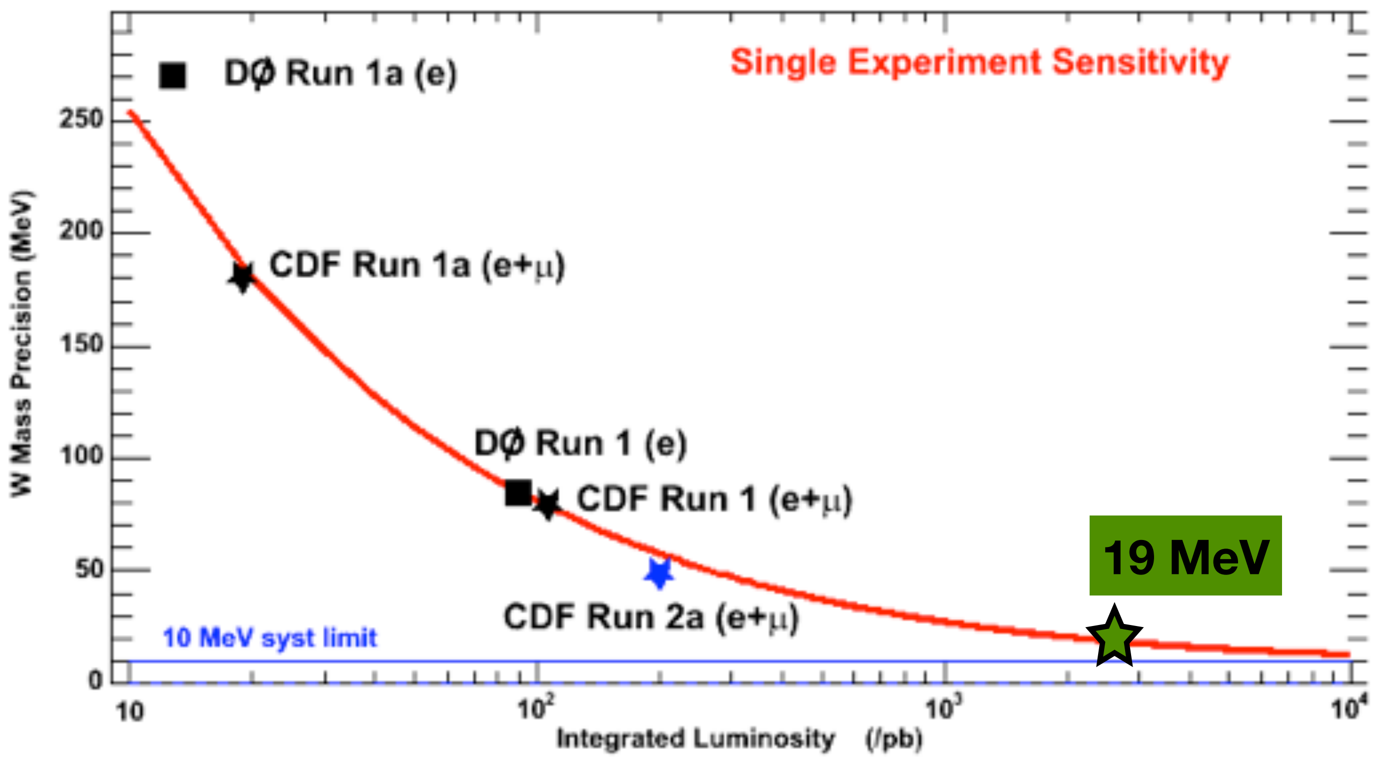
L (fb^{-1})	$H \to \gamma\gamma$	$H \to WW$	$H \to ZZ$	$H \to bb$	$H \to \tau\tau$	$H \to Z\gamma$	$H \to$ inv.
300	[6, 12]	[6, 11]	[7, 11]	[11, 14]	[8, 14]	[62, 62]	[17, 28]
3000	[4, 8]	[4, 7]	[4, 7]	[5, 7]	[5, 8]	[20, 24]	[6, 17]

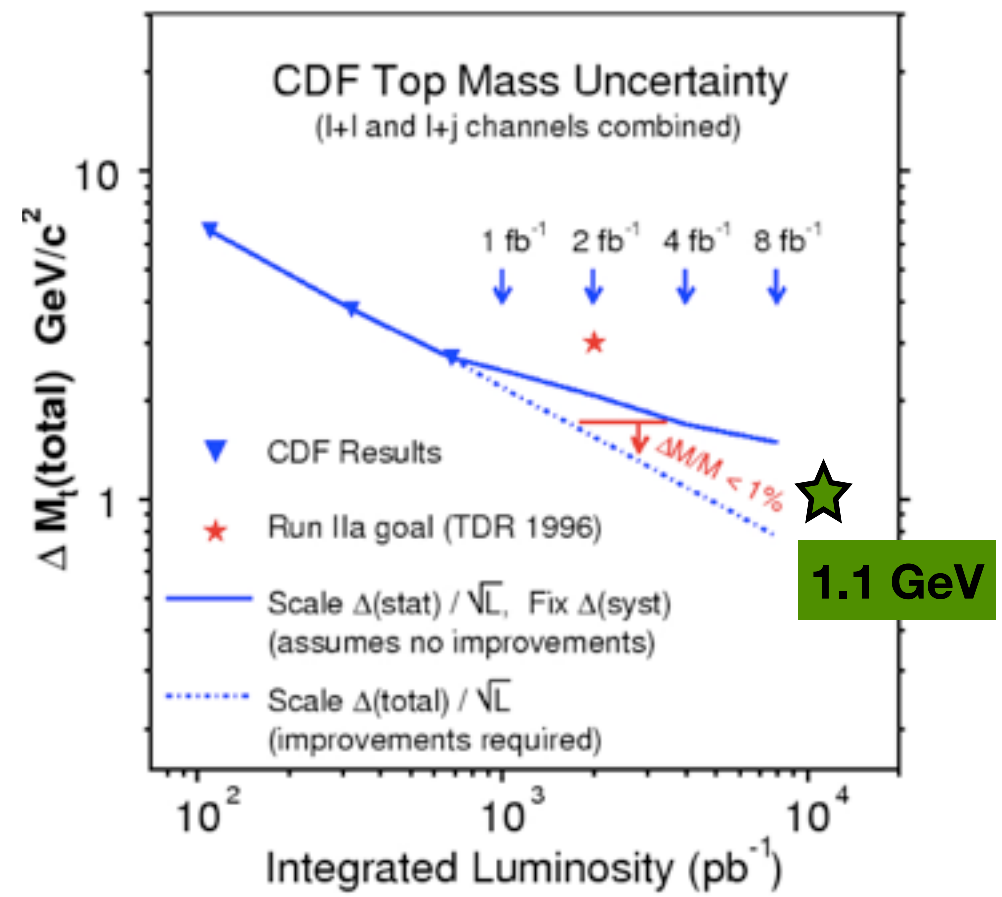
Assumptions on systematic uncertainties
Scenario 1: no change
Scenario 2: Δ theory / 2, rest ∝ 1/√L

Based on parametric simulation

Extrapolated from 2011/12 results

Projections in HEP





Assumptions on systematic uncertainties
Scenario 1: no change
Scenario 2: Δ theory / 2, rest $\propto 1/\sqrt{L}$

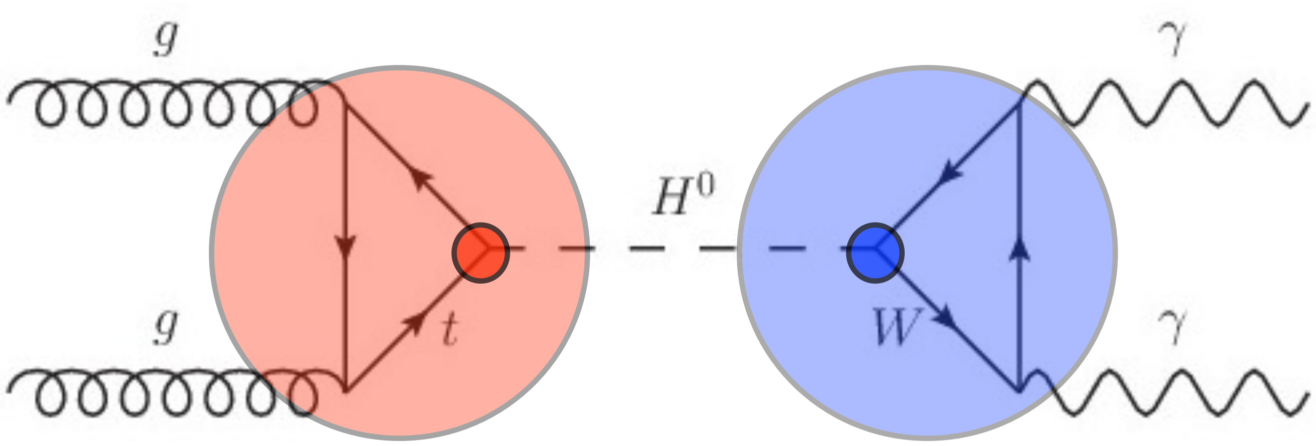
Large statistics allows to:
- be selective, use your best events.
- calibrate data *in situ*.

Theory calculations are work in progress, e.g. Annastasio et al working on NNNLO, PDF constrains from LHC data.

Higgs Boson Coupling Modifier Fits

$$(\sigma \cdot \mathrm{BR})(ii \to \mathrm{H} \to ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_H}$$

Effective theory approach. Fit deviation from the SM expectation.



$$(\sigma \cdot \mathrm{BR})(gg \to \mathrm{H} \to \gamma\gamma) = \kappa_g^2 \sigma_{\mathrm{SM}}(gg \to \mathrm{H}) \cdot \frac{\kappa_\gamma^2}{\kappa_\mathrm{H}^2} \mathrm{BR}_{\mathrm{SM}}(\mathrm{H} \to \gamma\gamma)$$

Higgs Boson Coupling Modifier Fits

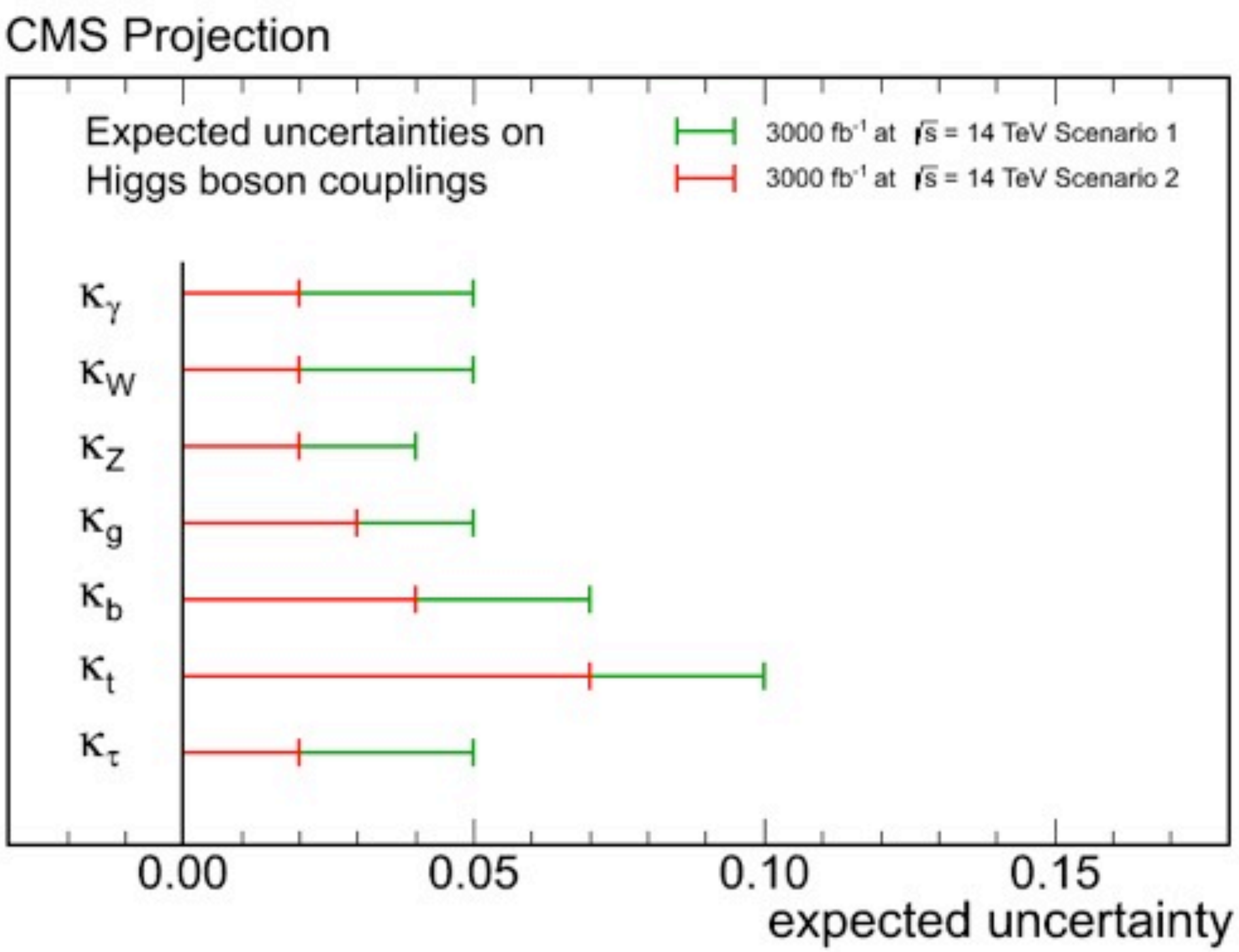
κ_g, κ_γ, $\kappa_{Z\gamma}$: loop diagrams ➜ allow potential new physics
κ_W, κ_Z: vector bosons
κ_t, κ_b: up- and down-type quarks
κ_τ, κ_μ: charged leptons
total width from sum of partial widths

alternatively:

$$\Gamma_{\text{tot}} = \sum \Gamma_{ii} + \Gamma_{\text{BSM}}$$

$$\text{BR}_{\text{BSM}} = \Gamma_{\text{BSM}} / \Gamma_{\text{tot}}$$

assumption here κ_W, $\kappa_Z < 1$



CMS Projection

L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	BR_{inv}
300	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]	[41, 41]	[14, 18]
3000	[2, 5]	[2, 5]	[2, 4]	[3, 5]	[4, 7]	[7, 10]	[2, 5]	[10, 12]	[7, 11]

* additional channels under study, e.g. ttH, H to VV

coupling precision 2-10 %
factor of ~2 improvement from HL-LHC

Precision Higgs Measurement

Imagine we do not find new (Higgs) particles in LHC data.

How large are deviations to couplings from BSM?

Deviations studied in numerous articles, e.g Gupta & Wells, arXiv:1206.3560.

They studied three types of models,

SUSY,

mixed-in hidden sector,

and composite Higgs bosons.

	ΔhVV	$\Delta h\bar{t}t$	$\Delta h\bar{b}b$
Mixed-in Singlet	6%	6%	6%
Composite Higgs	8%	tens of %	tens of %
Minimal Supersymmetry	< 1%	3%	10%[a], 100%[b]

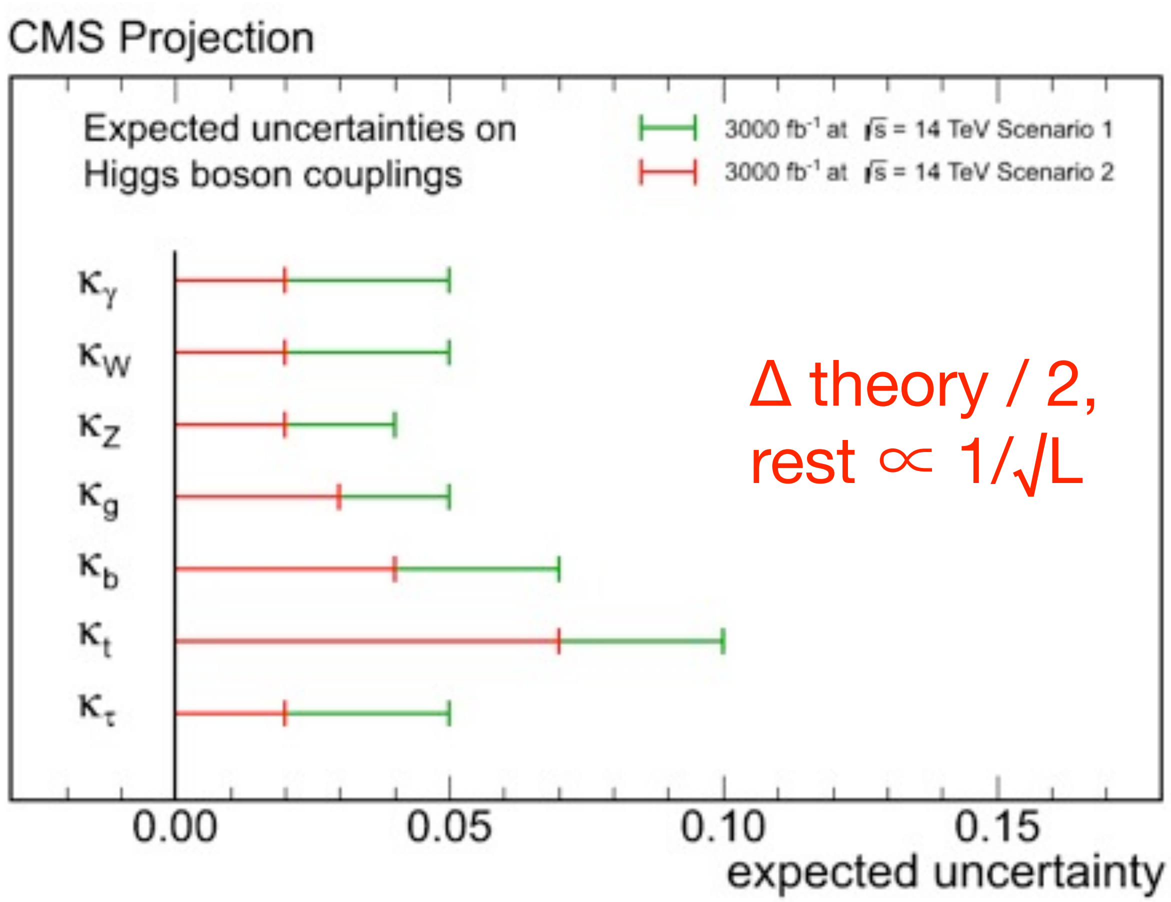
Conclusion, they find 1-10% deviations for vector bosons and few percent to tens of percent for fermion couplings.

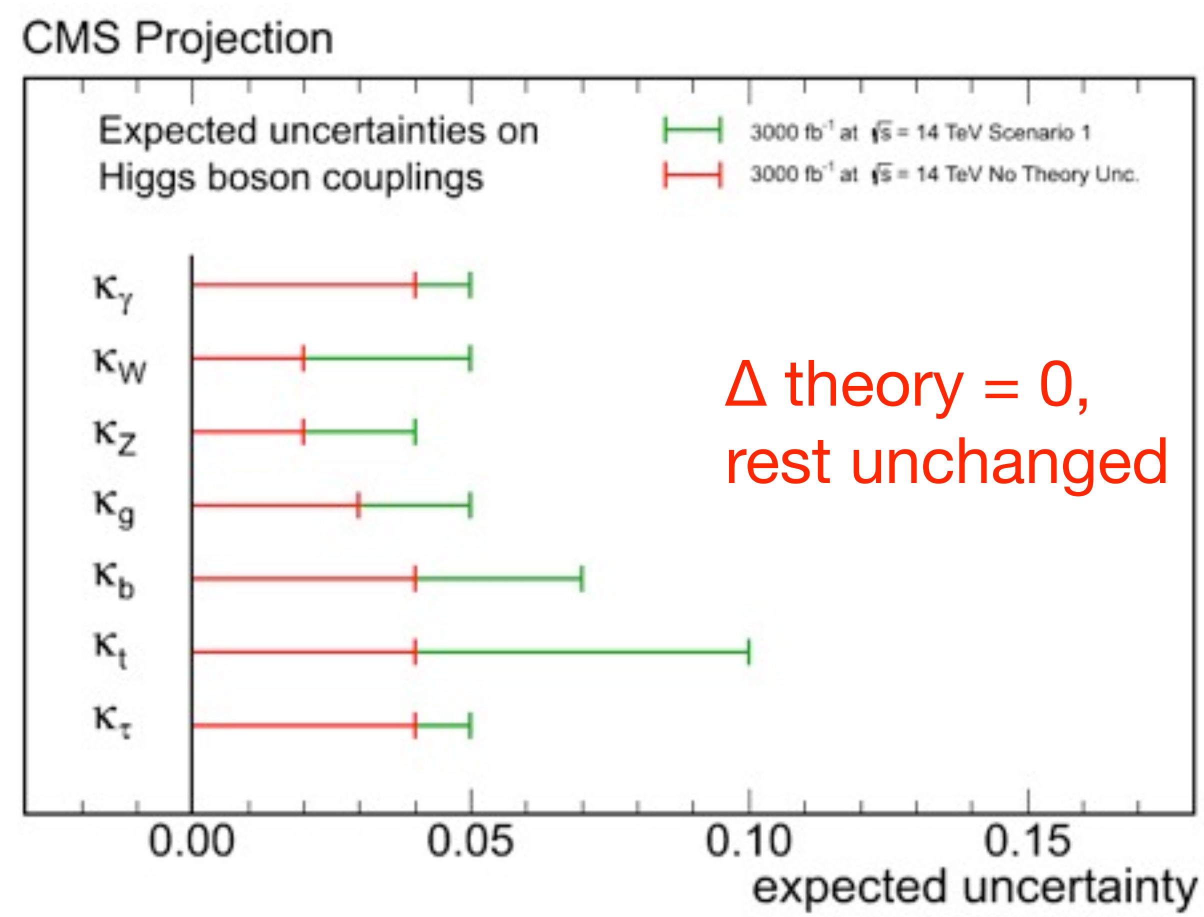
Most popular, MSSM Higgs sector in decoupling limit (large mA)

Theoretical Uncertainties

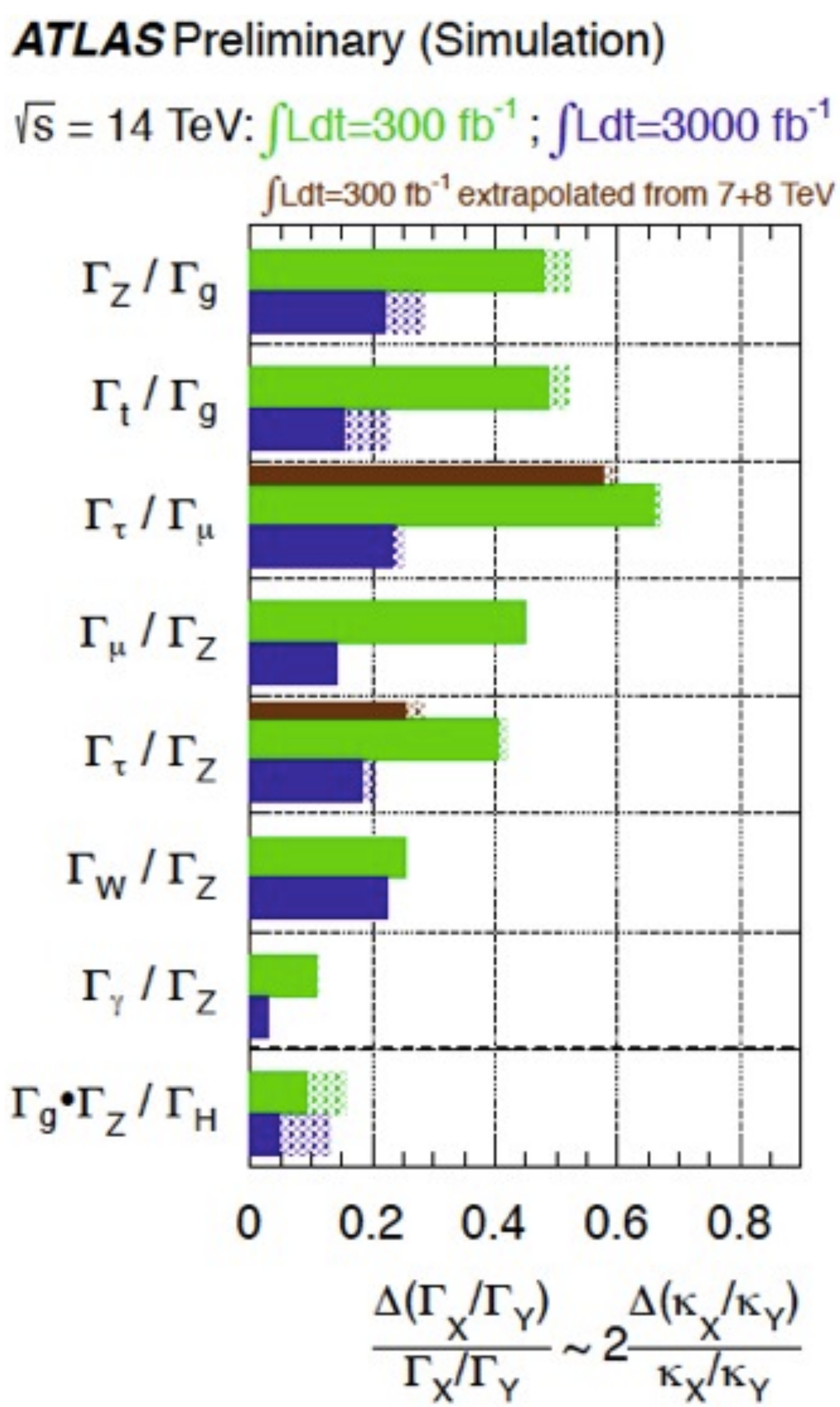
To test the importance of theoretical uncertainties we show the effect of removing them.

Theoretical uncertainties dominated by QCD scale and PDF uncertainties. Uncertainty on BR become relevant at few % precision.





Ratio measurements



No assumption on total width required for ratios of coupling parameters.

Ratios of partial widths are related to couplings via $\Gamma_X/\Gamma_Y = \kappa_X/\kappa_Y$.

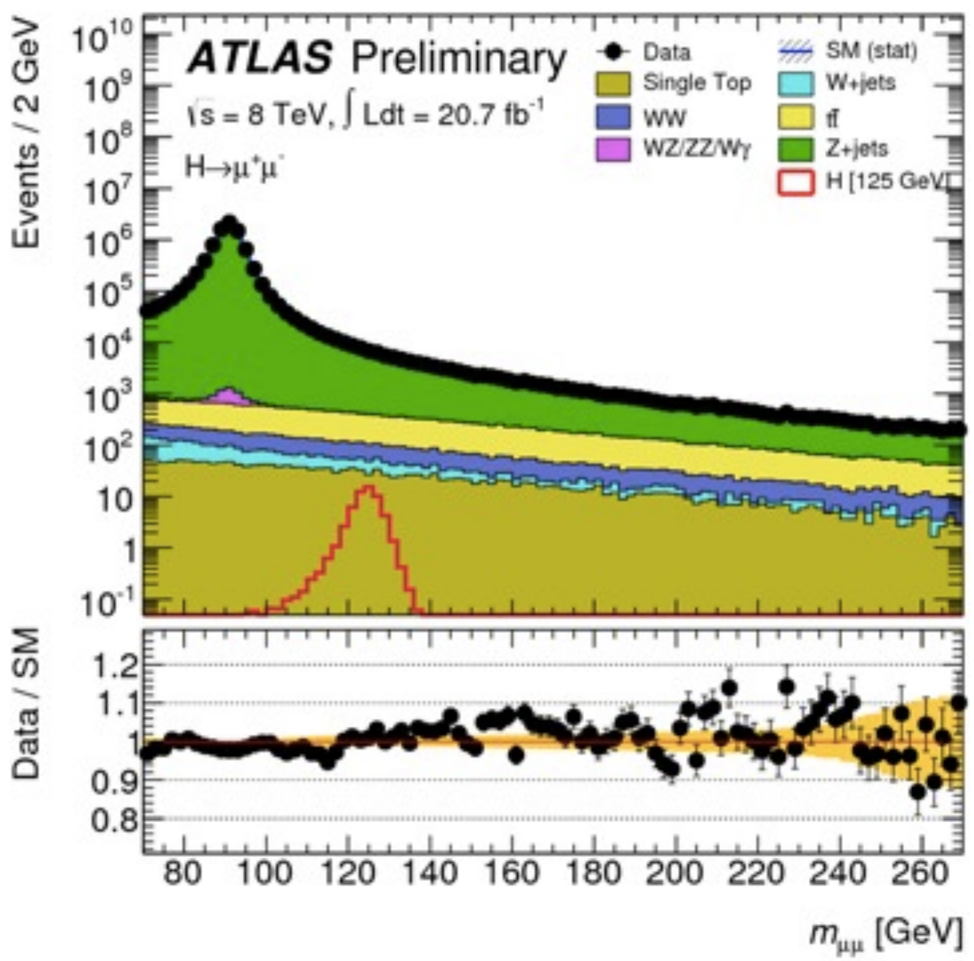
Theoretical uncertainty important also for ratio measurements

	3000 fb^{-1}	
	w/theory uncert.	wo/theory uncert.
Γ_Z/Γ_g	0.28	0.22
Γ_t/Γ_g	0.23	0.15
Γ_τ/Γ_μ	0.25	0.23
Γ_τ/Γ_μ (extrap)		
Γ_μ/Γ_Z	0.14	0.14
Γ_τ/Γ_Z	0.21	0.18
Γ_τ/Γ_Z (extrap)		
Γ_W/Γ_Z	0.23	0.23
Γ_γ/Γ_Z	0.029	0.029
$\Gamma_g \bullet \Gamma_Z/\Gamma_H$	0.13	0.047

Rare Decays - H → μμ

Small BR(H→μμ) = 2.2×10^{-4}; very large background, good mass resolution ~1-2%

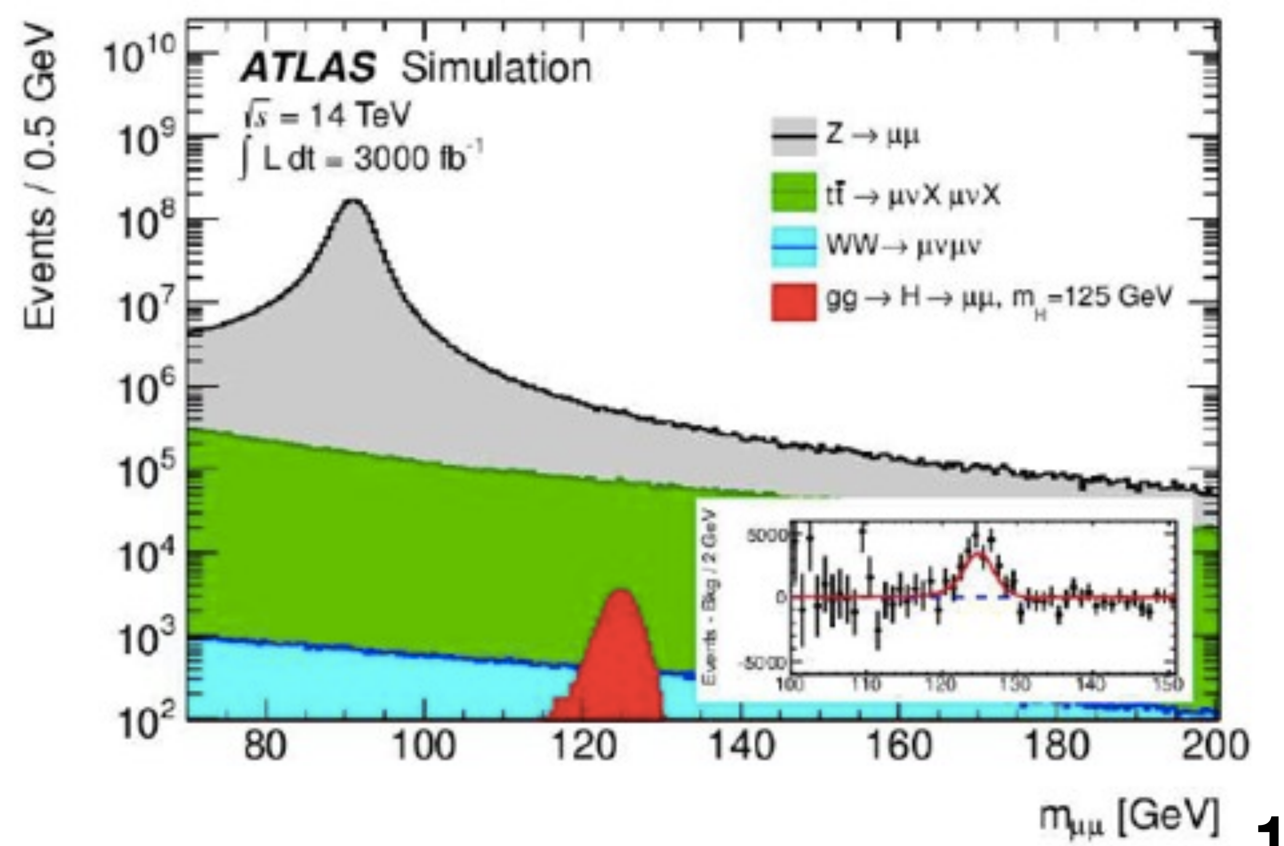
ATLAS result using 8 TeV dataset. 95% CL limit on σ x BR: 9.8 (8.2) observed (expected)



Requires very large dataset. Observation > 5σ expected in HL-LHC.

Interesting in ttH with S/B better than 1 and Δμ/μ ~ 25%.

Allows ratio of 2nd and 3rd generation lepton coupling.



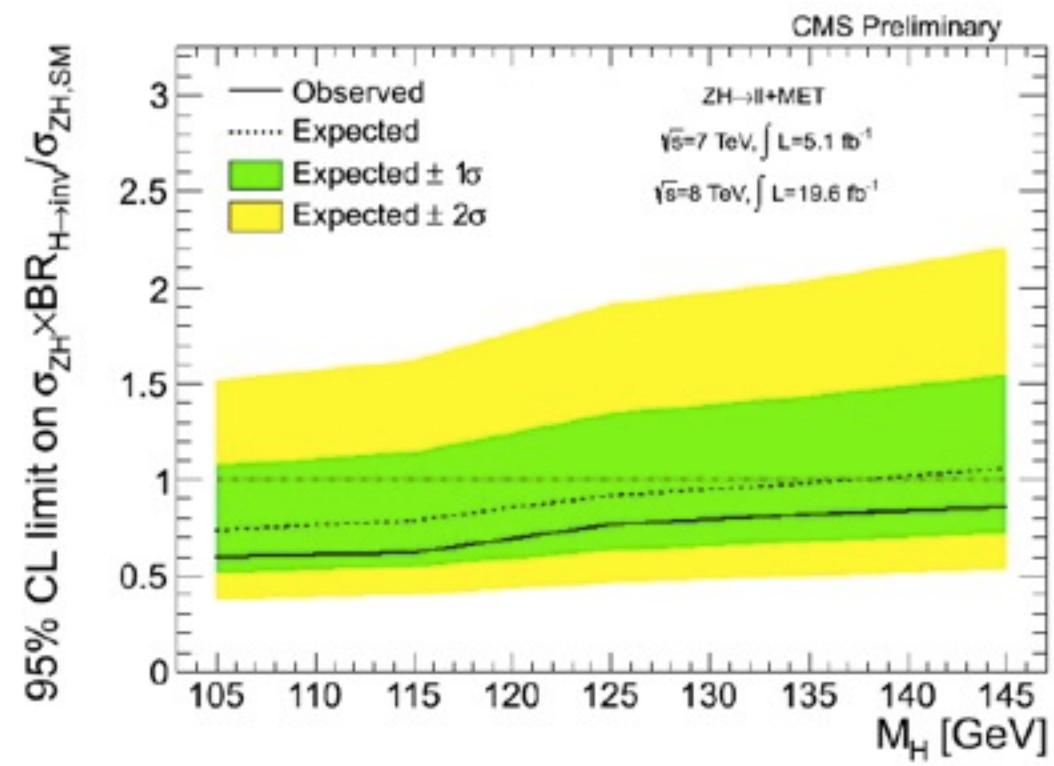
Invisible Higgs Decays

Accessible via VBF and ZH production.

Results available from ATLAS and CMS using ZH production. Assuming SM production cross section, observed (expected) 95% CL limits are

ATLAS: BR_{inv} < 65% (81%)

CMS: BR_{inv} < 75% (95%)



Estimate from CMS for future performance based in ZH analysis

L (fb^{-1})	$H \to inv.$
300	[17, 28]
3000	[6, 17]

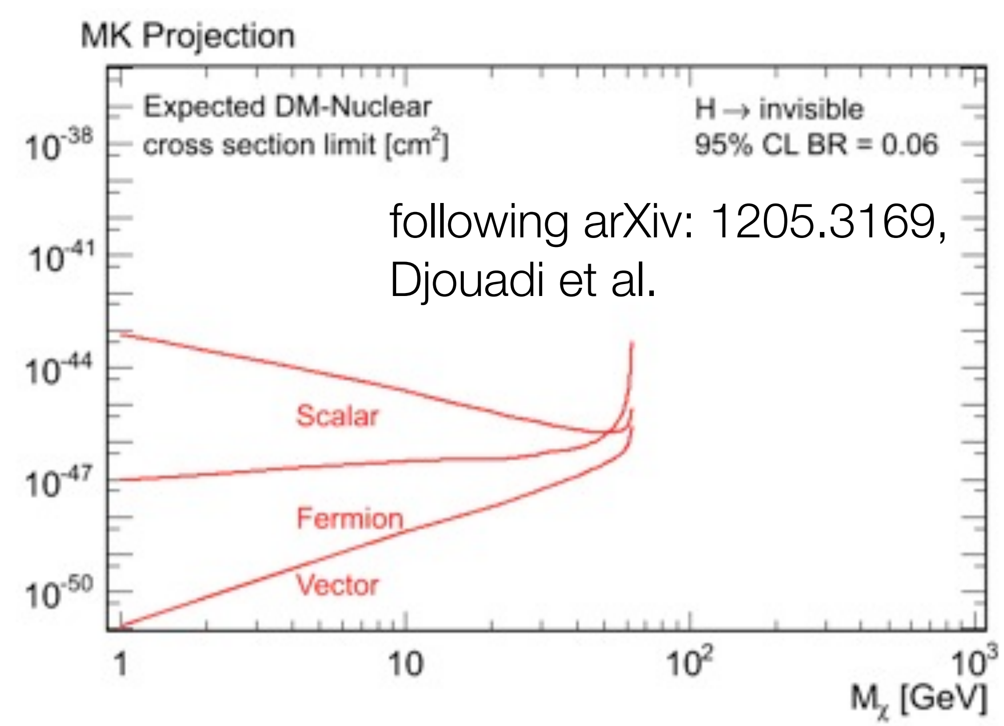
Extended Higgs coupling fit has sensitivity to BR_{BSM}

L (fb^{-1})	BR_{inv}
300	[14, 18]
3000	[7, 11]

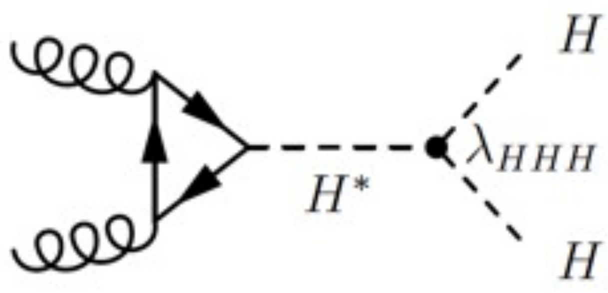
$$\Gamma_{\text{tot}} = \sum \Gamma_{ii} + \Gamma_{\text{BSM}}$$

$$BR_{\text{BSM}} = \Gamma_{\text{BSM}} / \Gamma_{\text{tot}}$$

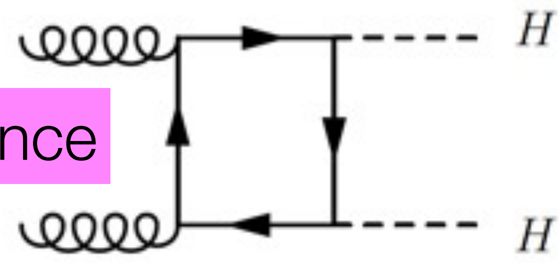
Connection to Dark Matter searches



Higgs Self-Coupling



interference



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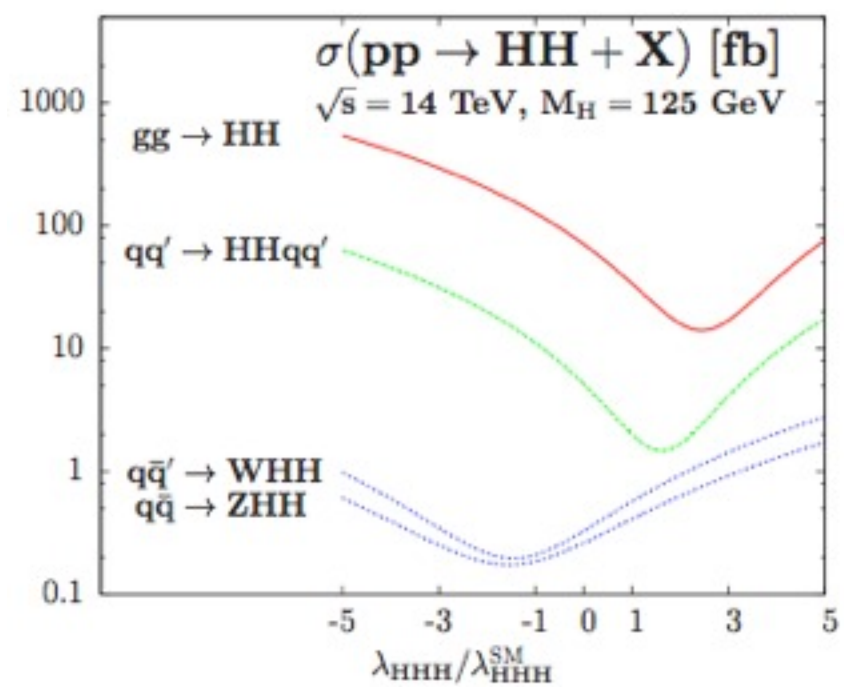
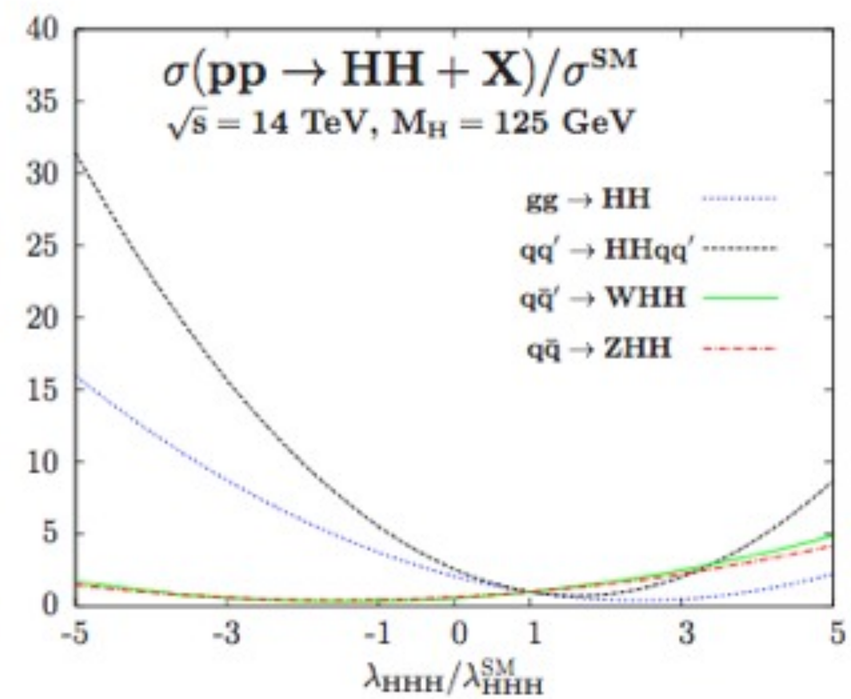
- Florian Goertz, Andreas Papaefstathiou, Li Lin Yang, José Zurita http://arxiv.org/abs/1301.3492

$\sqrt{s}$ [TeV]	$\sigma^{NLO}_{gg\to HH}$ [fb]
8	8.16
14	33.89





Interesting channels:

HH ➞ bbγγ

HH ➞ bbττ

HH ➞ bbWW

Needs further investigation by ATLAS and CMS; expected precision is ~30%

CP Mixture

H→VV coupling:

$$\mathscr{A}(X \to V_1 V_2) \propto \underbrace{a_1 m_V^2 \epsilon_1 \epsilon_2}_{\text{SM LO}} + \underbrace{a_2 f^1_{\mu\nu} f^{2,\mu\nu}}_{\text{SM NLO and BSM 0+ (assumed 0)}} + \underbrace{a_3 f^1_{\mu\nu} \tilde{f}^{2,\mu\nu}}_{\text{BSM 0-}}$$

$$f_{a3} = \frac{|a_3|^2\,\sigma(a_1=0,a_2=0,a_3=1)}{|a_1|^2\,\sigma(a_1=1,a_2=0,a_3=0)+|a_2|^2\,\sigma(a_1=0,a_2=1,a_3=0)+|a_3|^2\,\sigma(a_1=0,a_2=0,a_3=1)}$$

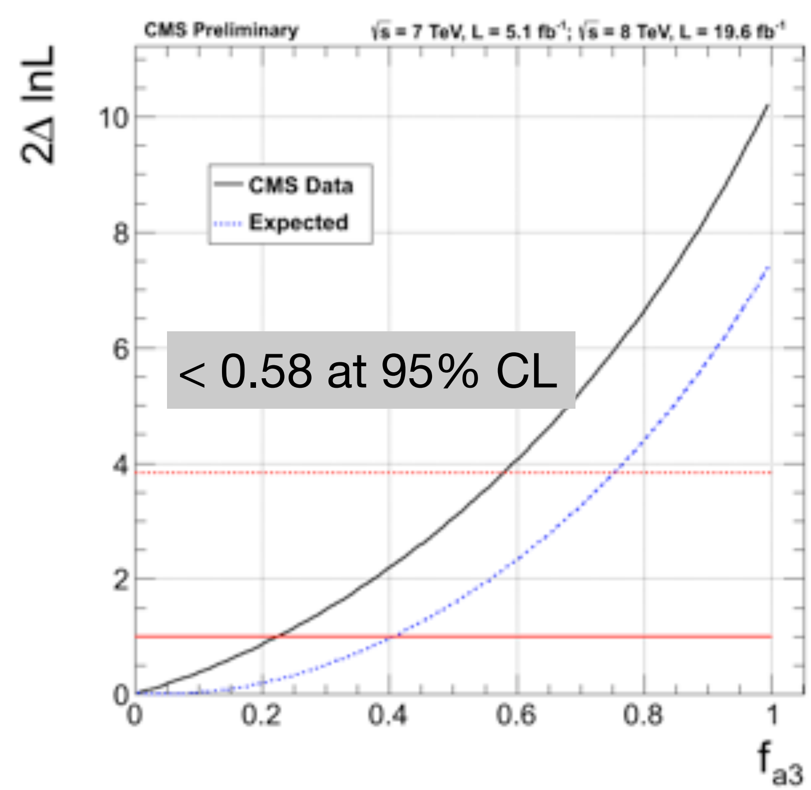
$$P_{sig}(m_{ZZ}, m_Z, m_{Z*}, \cos\theta_1, \cos\theta_2, \Phi, \Phi_1, \cos\theta^* ; f_{a2}, f_{a3}, \varphi_{a2}, \varphi_{a2})$$

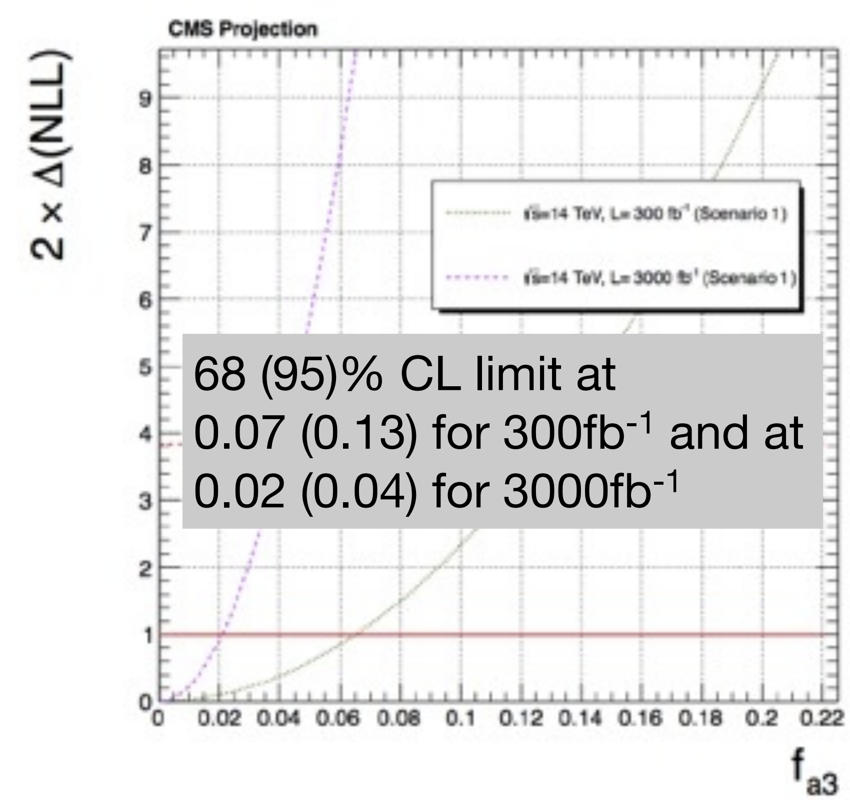
Pseudoscalar coupling and with that sensitivity to CP admixture suppressed.

Observable of mixture nearly identical for any phase, which warrants to fit of f_{a3} only.

More advanced CP mixing studies under development.

Potential for H→ff coupling needs further investigation.





Conclusion

HL-LHC provides excellent opportunity for Higgs precision measurements.

Coupling measurements with 2-10% precision.

L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	BR_{inv}
300	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]	[41, 41]	[14, 18]
3000	[2, 5]	[2, 5]	[2, 4]	[3, 5]	[4, 7]	[7, 10]	[2, 5]	[10, 12]	[7, 11]

Sensitivity to invisible or undetectable Higgs decays. Indirect 95%CL BR_{BSM}= [7,11]%, direct 95%CL BR_{inv}= [6,17]%

Higgs self-coupling needs further investigation, expected precision of ~30%.

BSM Higgs sector might reveal itself through precision measurements or via a new particle already in next LHC run.

Upgrade of ATLAS and CMS essential to reach full potential.

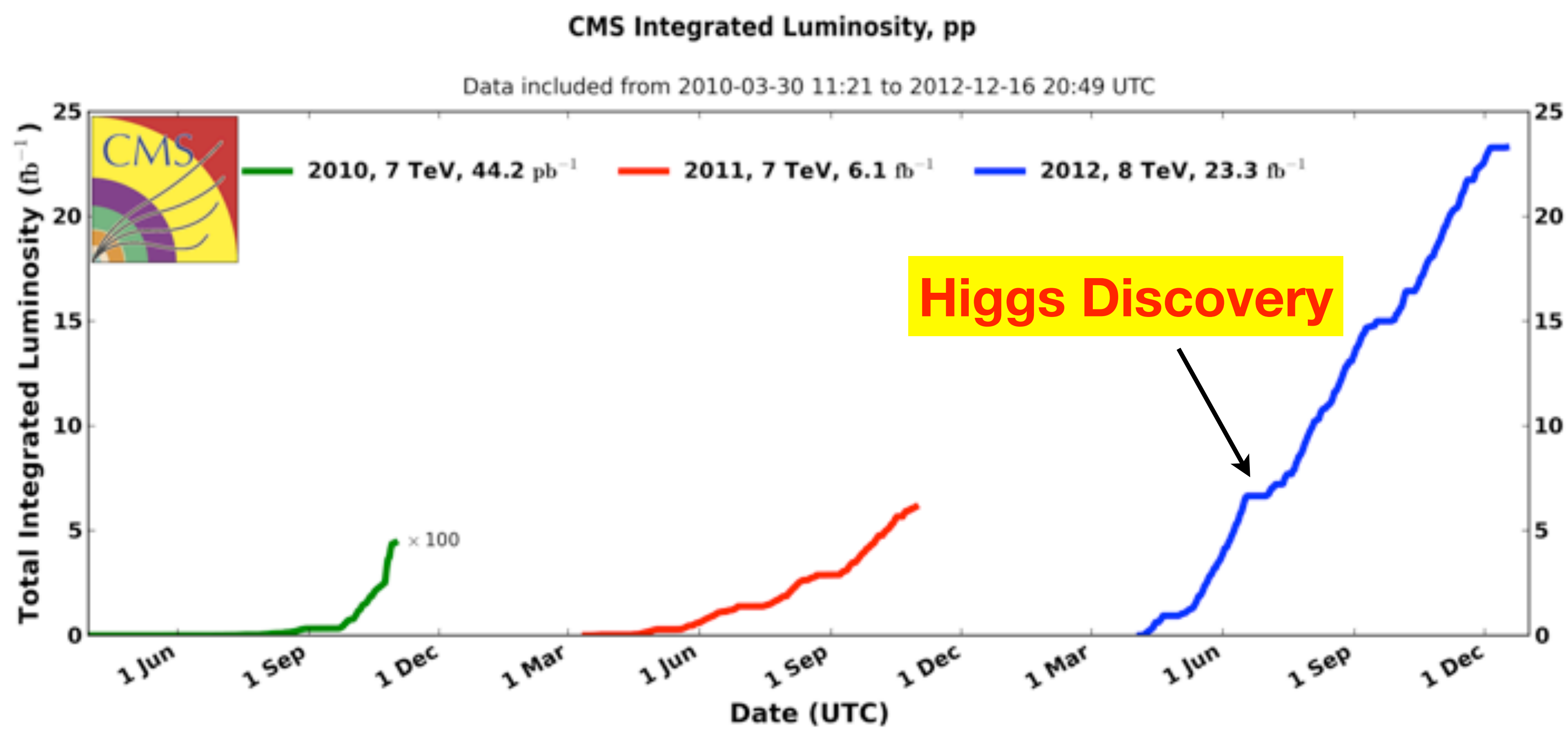
Status of Higgs Physics Program

Channel	ATLAS Lumi [1/fb]	CMS Lumi [1/fb]	Specialty	Inclusive signature	σ Obs. (Exp.)	mass [GeV]	Signal Strength μ	Spin/ Parity
$H \to ZZ \to 4l$	4.6+20.7	5.1+19.6	mass, discovery, spin/parity	4 leptons	6.6 (4.4)	124.3 ±0.6 (stat) ±0.5 (sys)	1.5 ± 0.4	√
					6.7 (7.2)	125.8 ±0.5 (stat) ±0.2 (sys)	0.91+0.30-0.24	√
$H \to WW \to 2l2\nu$	4.6+20.7	4.9+19.5	cross section, coupling	2 leptons, MET	3.8 (3.7)	consistent	0.99+0.31-0.32	√
					4.0 (5.1)	consistent	0.76 ± 0.21	√
$H \to \gamma\gamma$	4.8+20.7	5.1+19.6	mass, discovery, couplings	two photons	7.4 (4.3)	126.8 ±0.2 (stat) ±0.7 (sys)	1.55+0.33-0.28	√
					3.2 (4.2)	125.4 ±0.5 (stat) ±0.6 (sys)	0.78+0.28-0.26	-
$H \to bb$	4.7+20.3	5.0+19.0	coupling to fermions	two b-jets	-	consistent	0.2+0.7-0.6	-
					2.1 (2.1)	consistent	1.0 ± 0.4	-
$H \to \tau\tau$	4.6+13.0	4.9+19.4	couplings to leptons	hadronic taus, leptons, MET	1.1 (1.7)	consistent	0.8 ± 0.7	-
					2.9 (2.6)	120+9-7	1.1 ± 0.4	-

LHC Status and Plans

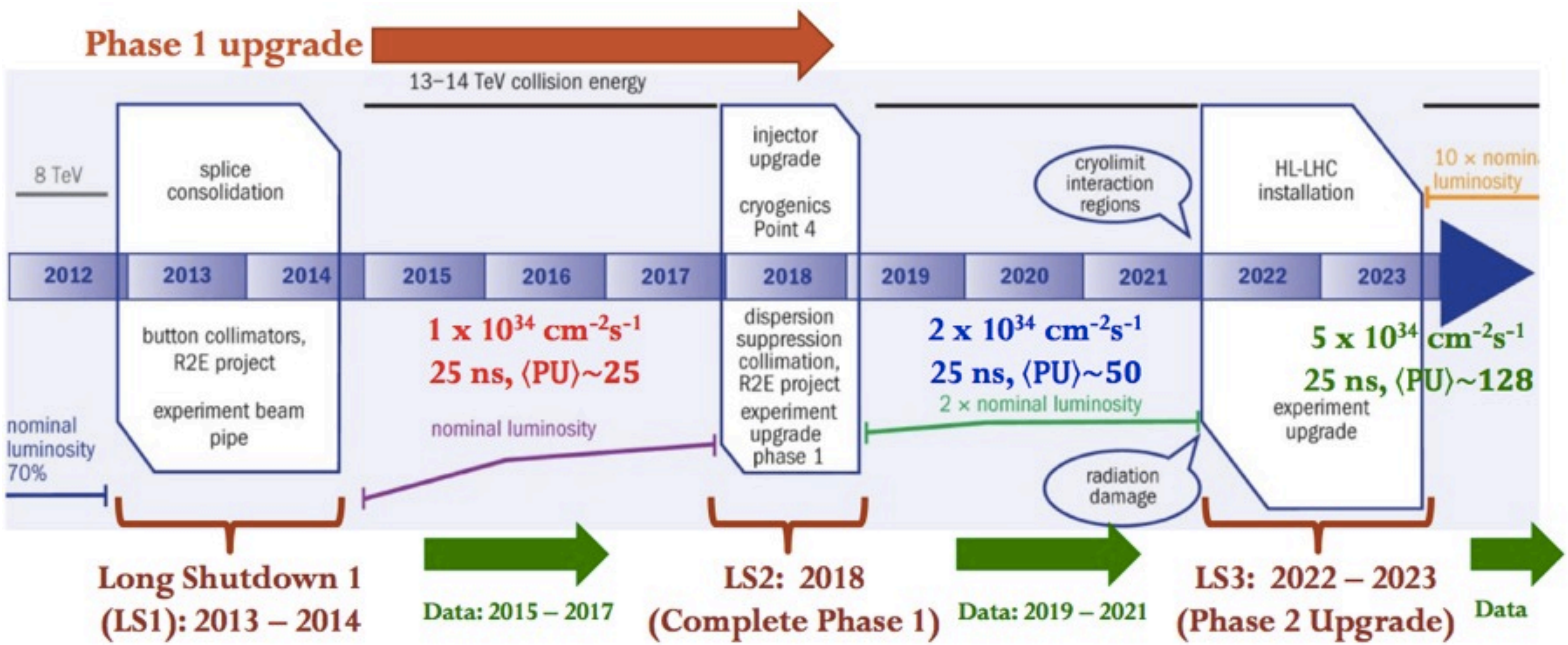
Amazing LHC performance with robust detector operation led to the historic discovery of a Higgs boson

The detailed study of this new particle will be a corner stone of the future LHC program



2010	2011	2012
7 TeV	7 TeV	8 TeV

LHC Upgrade Stages



LHC

Reach $10^{34}cm^{-2}s^{-1}$ by LS2, double by LS3 and integrate $300fb^{-1}$ by 2022

<PU> = 50

HL-LHC

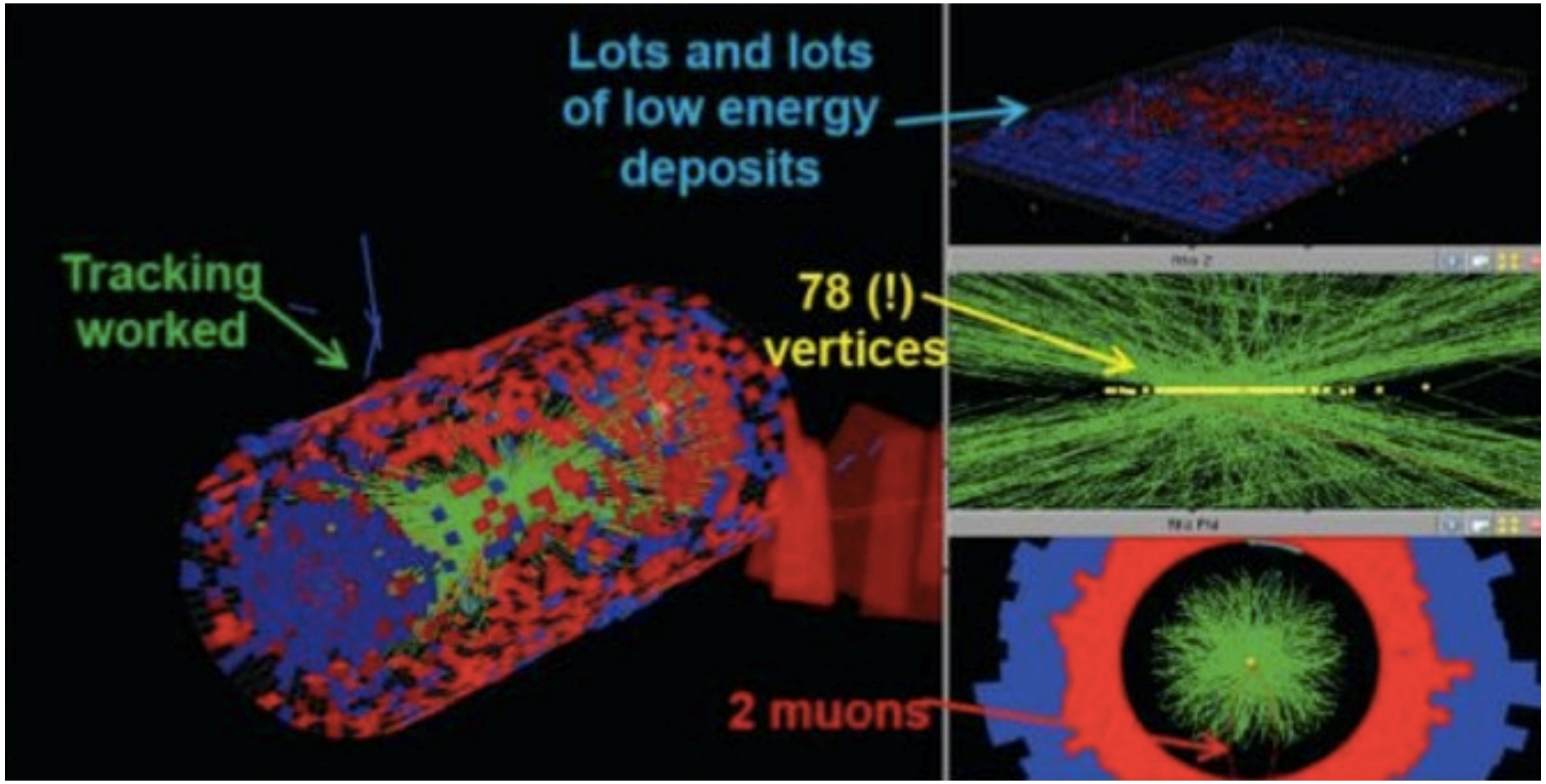
Lumi-level 5x $10^{34}cm^{-2}s^{-1}$ and integrate $3000fb^{-1}$after L3

<PU> = 140

Experimental Goals

Physics: precision measurements at the EWK scale while searching for new particles up to the multi-TeV scale.
Detector: extend and enhance detector capability, especially in the forward region where effects of PU and radiation are most severe
Pile-up: achieve robustness with up to 6x higher pile-up
Trigger: maintain low thresholds to support physics goals

Requires significant upgrades for ATLAS and CMS



LS1 and Phase I Upgrade Plans

ATLAS:

- Insertable B-Layer (IBL) silicon pixel detector
- Completing coverage by installing muon chamber
- Repairs to TRT and calorimeter

- Fast tracker (FTK) uses associated mem to find and fit tracks
- Muon New Small Wheel (NSW) upgrade to maintain tracking and trigger performance in $1.3 < |\eta| < 2.4$
- Upgrade calorimeter readout electronics to improve trigger

CMS:

- Complete muon coverage and improve trigger and electronics
- Colder tracker operating point
- Partial replacement of photodetectors in hadronic calorimeter
- New beampipe and infrastructure upgrade

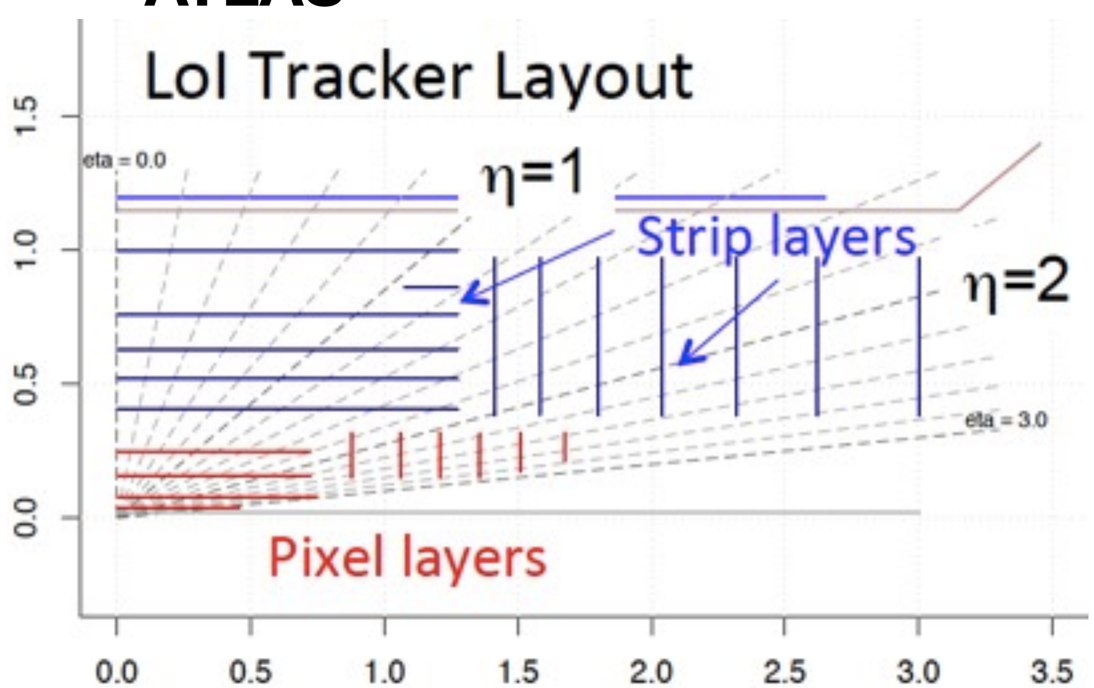
- Level 1 trigger upgrade
- New silicon pixel detector
- HCal photodetector and electronics upgrade

Phase II Upgrade Plans for ATLAS and CMS

Challenge: **longevity** due to radiation damage, **pile-up**

- Extensive redesign of **trigger system**
- Replacement of **tracking detectors**
- **Calorimeter** upgrades: electronics and new forward detectors
- **Muon detector** upgrades
- Software and computing upgrades to cope with large data volume

ATLAS



CMS Phase II tracker proposal